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Enhanced infiltration regime for treated-wastewater purification in soil aquifer treatment (SAT)

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SUMMARY

Utilization of treated wastewater (TWW) for agriculture is a widely accepted practice in regions suffering from freshwater (FW) shortages. Soil aquifer treatment is often employed for wastewater purification in regions with sandy soil. Infiltration rates of water through the soil can decrease as a result organic matter (OM) accumulation and the consequential water repellency. We examined several infiltration regimes with the aim of achieving lower levels of OM accumulation, reduced water repellency and increased infiltration rate in the topsoil layer of the infiltration basin. OM accumulation in the topsoil layer was found to be the main factor adversely affecting soil permeability. In measurements performed in the infiltration basins of the Tel Aviv wastewater-purification facility over a 1-year period, infiltration rates were found to differ with season, being low in the winter and high in the summer. Similar observations were made on small model infiltration ponds established to simulate the large basins. Several water-application regimes were tested for enhancement of the infiltration rates. Rapid application of TWW was the most efficient method in terms of reducing OM accumulation and water repellency in the topsoil layer. Low-rate, and spraying of TWW over the soil using sprinklers produced the highest OM accumulation and consequently, higher water repellency. Low-rate, single outlet application—the conventional infiltration method employed in the commercial infiltration basins—exhibited moderate OM accumulation and water repellency. Neither water repellency nor OM accumulation were observed in the FW-application regime. Accumulation of OM originating from the percolating TWW, at the topsoil layer was identified as dominating infiltration rate at the infiltration basins. Reduction of OM content by the means proposed and evaluated in this experiment can drastically increase infiltration rates.

1. Introduction

Freshwater (FW) shortages are common in many countries in the Middle East and Mediterranean region due to long periods of drought, population growth, and the concomitant rise in water demand. In Israel, about 90% of the raw sewage is treated in wastewater-treatment plants (WWTPs) and 65 to 70% of the treated wastewater (TWW) is reused. Most of this TWW is used for irrigation in agriculture (about 460×10^6 m^3 per year) and the rest is used for industry and nature preservation.

The Dan Region Reclamation Project (Shafdan) is the largest WWTP in Israel, treating about 130 million m^3 of raw wastewater annually originating from the city of Tel Aviv and surrounding municipalities. The Shafdan WWTP treats the raw sewage in activated-sludge bioreactors followed by secondary clarifiers. The secondary TWW is then further treated to tertiary TWW by slow sand filtration using soil aquifer treatment (SAT). The secondary TWW is allowed to infiltrate vertically into a cell in the coastal groundwater aquifer through a sandy soil layer of about 15–30 m followed by horizontal flow through the aquifer to recovery wells located 1–2 km away from the infiltration basins. The long retention time of the TWW in the soil facilitates biological activity, sedimentation, oxidation, reduction in viruses and bacteria and adsorption processes thereby improving effluent quality (Icekson-Tal et al., 2003). The tertiary TWW evolving in the groundwater is then pumped and transferred to the southern region of Israel for unrestricted irrigation. Hydraulic loading in each TWW-infiltration basin varies from 80 to 150 m/y according to the basin's capacity. The hydraulic loading is divided into a flooding period of nearly 24 h, and a drainage period of 48–72 h to allow the formation of aerobic conditions in the soil. It should be noted that several countries/

Abbreviations: FW, freshwater; HC, hydraulic conductivity; OM, organic matter; SAT, soil aquifer treatment; TWW, treated wastewater; WDPT, water-drop penetration time; WWTP, wastewater-treatment plant.

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areas in the Mediterranean region, including the north of Africa, which face scarcity in FW availability, are currently using SAT projects to increase their water resources (Lazarova et al., 2000).

During TWW infiltration through the soil layers, the dissolved organic carbon (DOC) concentration is reduced by 70–90% (Lin et al., 2008). Polysaccharides, proteins and humic substances are largely removed during the TWW percolation through the soil under anoxic conditions (Amy and Drewes, 2007).

TWW is chemically different from FW, mainly due to its OM content. Representative OM contents, expressed in terms of chemical oxygen demand, in raw sewage and primary and secondary effluents are: 250–1000, 150–750 and 30–60 mg/L, respectively (Chen et al., 2009; Feigin et al., 1991). The addition of OM originating from TWW to soils can change their physicochemical properties. One of the physical effects resulting from TWW application in soils is water repellency (Chen et al., 2003; Arye et al., 2011; Lerner, 2002; Tarchitzky et al., 2007): a drop of water placed on a hydrophilic dry soil will spontaneously and immediately infiltrate. In contrast, in a water-repellent soil, infiltration will take time and the length of time required is called the water-drop penetration time (WDPT).

Water temperatures can also affect water infiltration into the soil, with high temperatures inducing high infiltration rates and vice versa (Jaynes, 1990). Lin et al. (2003) showed a correlation between lower temperatures and low infiltration rates in the winter, and high infiltration rates at the high temperatures prevailing in the summer. This seasonal pattern repeated itself in the four consecutive years of their experiment. The lower infiltration rates in the winter were attributed to increased water viscosity resulting from the low temperatures. However, the increase in infiltration rate with water temperature was reported to be about 150–200% higher than the decrease in viscosity when the TWW warmed up, suggesting the involvement of additional temperature-dependent factors (Lin et al., 2003).

Water movement and retention in water-repellent soils is different from that in fully wettable soils, even after the water has penetrated the repellent soil. While in wettable soils, infiltration rates decrease with time, in water-repellent soils, infiltration rate often tends to increase with time (DeBano, 1969; Feng et al., 2001; Arye et al., 2011; Magesan et al., 1999). In addition, the final infiltration rate in a water-repellent soil can be one order of magnitude lower than that in a similar yet wettable soil (Wallis et al., 1991). Viviani and Iovino (2004) found an up to 50% reduction in soil hydraulic conductivity (HC) and an increase in total suspended solids from 0 to 50 mg/m^2 in a 49% clay soil. Low soil permeability can also be induced by a high water head at the soil surface that induces soil compaction (Houston et al., 1999): a water head of up to 600 mm and short flooding periods of up to 3 days were found effective in preventing the reduction in soil permeability (Houston et al., 1999). On the other hand, increasing the hydraulic head at the surface of a water-repellent soil can raise its HC back to the soil's original level (before it turned repellent) (Feng et al., 2001). In addition, a higher hydraulic head in a water-repellent soil can significantly reduce the preferential flow effect in the soil profile (Carrillo et al., 2000a).

Chen et al. (2009) and Arye et al. (2011) found that long-term application of TWW in the infiltration basins of the Shafdan WWTP had resulted in OM accumulation in the topsoil layer. As a consequence, water repellency and alteration of the hydraulic properties in the topsoil of these basin layers occurred. The main objective of the present study was to further explore the induction and establishment of water repellency and define an alternative regime (to the company's current approach) for the Shafdan WWTP infiltration basins. Secondary aims were to characterize the soil and hydraulic properties of the infiltration basins used at the Shafdan WWTP, and to propose an alternative infiltration regime that may increase infiltration rates and serve the company operating the site (Mekorot, the national water supply company) in the future.

2. Materials and methods

2.1. Infiltration basins

In the Shafdan WWTP, raw sewage is treated by primary treatment followed by an aerobic activated-sludge process and clarifiers. The secondary effluent is then allowed to infiltrate the soil through infiltration basins into the groundwater aquifer. Two concentric circles of pumping wells surround the infiltration basins. The first is used to pump and sample groundwater near the infiltration basin and the second, at a distance of 1–2 km, is used to pump irrigation water to be delivered to pre-irrigation reservoirs situated about 70–80 km south of the WWTP. There are several infiltration sites along the sandy coastline south of the Shafdan WWTP. For this experiment, we chose the Sorek site near the city of Rishon Lezion, Israel. This site consists of four infiltration basins, each divided into four to five sub-basins, located on a sand dune soil. Each sub-basin has an area of 6 to 16 $\times$ 10^3 m^2. Each basin is filled with secondary TWW from the Shafdan WWTP from a single outlet at the basin edge which is operated for 24 h, followed by 48 to 72 h of drainage. This infiltration regime is hereafter referred to as "Shafdan regime". While one basin is being filled, the others are being drained, based on a 4-day cycle. Our experiments were conducted in basin 102–1 (basin 102, sub-basin 1).

Basin 102-1 is 120 m $\times$ 50 m and >2 m deep. Over a period of 1 year (September 2007–September 2008), OM content, HC and WDPT values were measured in the topsoil layer of this basin. The measurements were conducted at three locations along the basin (20, 70 and 140 m from the water outlet) at its surface.

2.2. Model infiltration ponds

The aim of this research was to investigate the management of the infiltration basins with a focus on water repellency and flooding regime. To achieve enhanced infiltration rates and overcome the main problem of soil water repellency, a suitable management regime needs to be identified. Four model infiltration ponds (5 $\times$ 3 m and 1 m deep) were built at the Shafdan WWTP site, designed to simulate the large infiltration basins. The four ponds were built on a sandy soil with almost no clay or silt fractions (clay + silt < 1%). The walls of the ponds were covered with polyethylene sheets to prevent horizontal water flow.

The model ponds were exposed to flooding (infiltration) and drainage cycles. In each infiltration cycle, all ponds were simultaneously filled with 24 m^3 of TWW or FW water according to the treatments applied (Table 1), followed by a 72-h drainage period. This flooding/drainage cycle was identical to that applied in the large infiltration basins by the company operating the WWTP. Three additional treatments are also presented in Table 1. The experiment started in March 2007 and was conducted continuously until the end of July 2008.

TWW quantity in each pond at each flooding cycle was controlled by a water gauge connected to the main control box. A pressure-head gauge (transducer) was placed in the middle of each pond to measure and control the water level by opening or closing an electric valve. Soil, water and air temperatures were automatically measured during the experiment using temperature probes and the data were stored in the data logger.

The model ponds included a control pond and three treatment ponds (Fig. 1). The control pond (SO-FW) was filled with FW from a single outlet at a flow rate of 1 m^3/h, in accordance with the cur-